THE PHENOMENOLOGY OF SCALAR COLOUR OCTETS

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Abstract

We discuss the phenomenology of colour scalar octet particles. Namely, we consider the discovery potential of scalar octets at LEP, FNAL and LHC. Octet scalars decay mainly into two gluino and new hadrons composed from scalar coloured octets are rather longlived ($\Gamma \leq O(10) Kev$). For the scalar octet masses($M \geq O(50) Gev$) the scalar octets producing at FNAL or LHC will decay into two gluons that leads to additional four-jet events. We propose to look for the scalar octets by the measurement of the distributions of the four-jet differential cross section on the invariant two-jet masses. Scalar octets naturally arise in models with compactification of additional dimensions. In such models the branching ratio for the scalar octet bound state into 2 photons is $O(10^{-2})$ that leads to the events with two photons and two jets. We also point out that the current experimental data don't contradict to the existence of light ($M \sim O(1) Gev$) scalar octets. Light scalar colour octets give additional contribution to the QCD β -function and allow to improve agreement between deep inelastic and LEP data.

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The aim of this note is the discussion of the phenomenology of scalar colour octets. The relatively light ($M \leq O(1)Tev$) scalar colour octets are predicted in some nonsupersymmetric and supersymmetic GUTs [1, 2]. Here we consider the discovery potential of scalar octets at LEP, FNAL and LHC. Colour octet scalars decay mainly into two gluons with rather small decay width ($\Gamma \leq O(10)Kev$), so new hadrons composed from colour scalar octets are longlived. The scalar octets producing at FNAL or LHC (for scalar octet masses $M \geq O(50)Gev$) decay into two gluino that leads to additional four-jet events. We propose to look for scalar octets by the measurement of the distributions of the four-jet differential cross section on the invariant two-jet masses. At least, the accurate measurement of the four-jet differential cross section allows to extract the lower bound for the octet scalar cross section. Scalar octets naturally arise in models with compactification of additional dimensions. In such models the branching ratio for the scalar octet bound state into two photons is $Br(\Phi g \to \gamma\gamma) \sim O(10^{-2})$. For such models we shall have the events with two photons and two jets that allows to detect scalar octets using this mode. We also point out that the current experimental data don't contradict to the existence of light ($M \sim O(1)Gev$) scalar octets. Light scalar octets give additional contribution to the QCD β-function and allow to improve agreement between deep inelastic and LEP data.

To be precise in this paper we consider colour light scalar octets neutral under $SU(2) \otimes U(1)$ electroweak gauge group. Such particles are described by the selfconjugate scalar field $\Phi^\alpha_\beta(x)$ ($(\Phi^\alpha_\beta(x))^+ = \Phi^\beta_\alpha(x)$, $\Phi^\alpha_\alpha(x) = 0$) interacting only with gluons. Here $\alpha = 1, 2, 3$; $\beta = 1, 2, 3$ are $SU(3)$ indices. The scalar potential for the scalar octet field $\Phi^\alpha_\beta(x)$ has the form

$$V(\Phi) = \frac{M^2}{2} Tr(\Phi^2) + \frac{\lambda_1 M}{6} Tr(\Phi^3) + \frac{\lambda_2}{12} Tr(\Phi^4) + \frac{\lambda_3}{12} (Tr\Phi^2)^2 \tag{1}$$

The term $\frac{\lambda_1 M}{6} Tr(\Phi^3)$ in the scalar potential (1) breaks the discrete symmetry $\Phi \to -\Phi$. The existence of such term in the lagrangian leads to the decay of the scalar octet mainly into two gluons through one-loop diagrams similar to the corresponding one-loop diagrams describing the Higgs boson decay into two photons. One can find that the decay width of the scalar octet is determined by the formula

$$\Gamma(\Phi \to g\, g) = \frac{15}{4096\pi^3} \alpha_s^2 c^2 \lambda_1^2 M\,, \tag{2}$$

where

$$c = \int_0^1 \int_0^{1-w} \frac{wu}{1-u-w}\, du\, dw = 0.048 \tag{3}$$

and α_s is the effective strong coupling constant at some normalization point $\mu \sim M_z$. Numerically for $\alpha_s = 0.12$ we find that

$$\Gamma(\Phi \to gg) = 0.39 \cdot 10^{-8} \lambda_1^2 M \tag{4}$$

From the requirements that colour $SU(3)$ symmetry is unbroken (the minimum $\Phi^\alpha_\beta(x) = 0$ is the deepest one) and the effective coupling constants $\overline{\lambda}_2$, $\overline{\lambda}_3$ don't have Landau pole singularities up to the energy $M_0 = 100 \cdot M$ we find that $\lambda_1 \leq O(1)$. Therefore, the decay

width of the scalar colour octet is less than $O(10)ev, O(100)ev, O(1)Kev, O(10)Kev$ for the octet masses $M = 1$, 10, 100, 1000 Gev correspondingly. It means that new hadrons composed from scalar octet Φ, quarks and gluons ($\overline{q}\Phi q$, Φg, $qqq\Phi$ are longlived even for very high scalar octet mass.

Light scalar octets with the mass $M = O(several)\, Gev$ give additional contribution to the QCD β-function that changes evolution of the QCD effective strong coupling constant. For instance, in one-loop approximation we have the following formula [3, 4] for the effective strong coupling constant:

$$\alpha_s(Q) = \frac{4\pi}{b_0 ln(Q^2/\Lambda^2)}\,, \tag{5}$$

where $b_0 = 11 - \frac{2}{3}N_f$ for the standard case and $b_0 = 11 - \frac{2}{3}N_f + \frac{1}{2}$ for the case when we take into account light scalar octet in the loop. In complete analogy with the case of light gluino [5, 6] an account of light scalar octets leads to the modification of the strong coupling constant at the M_z scale extracted from low energy deep inelastic data and data on the τ-lepton decay width. Namely, one can find that the "modified" strong coupling constant taking into account the QCD evolution due to light scalar octet is

$$\alpha_s^{mod}(M_z) = \frac{1}{\frac{1}{\alpha_s(M_z)} - 0.08 ln(\frac{M_z}{M})} \tag{6}$$

For instance, for $\alpha_s(M_z) = 0.113$ extracted from deep inelastic data for $Q_0 = 5Gev$ we find that $\alpha_s^{mod}(M_z) = 0.1161;\ 0.1153;\ 0.1146;\ 0.1136$ for the scalar octet masses $M = 5;\ 10;\ 20;\ 30\, Gev$ correspondingly. So we find that the maximal effect is the increase of the effective strong coupling constant by 0.003 that is welcomed effect since it improves the agreement between strong coupling constant extracted from Z-boson total hadronic decay width and deep inelastic data. For the current situation with experimental determination of $\alpha_s(M_z)$ see ref.[7].

Consider now the possibility of the discovery of scalar octets at LEP1. For the scalar octets lighter than $\frac{M_z}{2}$ the differential decay width

$$Z(p) \rightarrow \overline{q}(p_1)q(p_2)\Phi(p_3)\Phi(p_4) \tag{7}$$

in the leading approximation on strong coupling constant $\alpha_s(M_z)$ for massless quarks is determined by the formula

$$d\Gamma(Z \rightarrow \overline{q}q\Phi\Phi) \cdot (\Gamma(Z \rightarrow hadrons))^{-1} = A\, dm_{12}^2 dp^2\,, \tag{8}$$

$$A = \frac{4\alpha_s^2}{3\pi^2 p^2}(1 - \frac{4M^2}{M_z^2})^{\frac{3}{2}} \cdot [BC^{-1} ln(\frac{C+D}{C-D}) - 2D] \tag{9}$$

Here α_s is the effective strong coupling constant at some normalization point $\mu \sim M_z$, $m_{12}^2 = (p_1+p_2)^2,\ p^2 = (p_3+p_4)^2$, $C = \frac{1}{2}(M_z^2+p^2-m_{12}^2)$, $B = C^2+\frac{1}{2}m_{12}^2(M_z^2+p^2)$, $D^2 = C^2 - M_z^2 p^2$. In our numerical estimates we shall take $\alpha_s = 0.12$. For the branching ratio $B = 10^3\Gamma(Z \rightarrow \overline{q}q\Phi\Phi) \cdot (\Gamma(Z \rightarrow hadrons))^{-1}$ our numerical results are presented in table 1. For light scalar octets ($M \sim O(several)\, Gev$) the process $Z \rightarrow \overline{q}q\Phi\Phi$ qives additional

contribution to the standard QCD four-jet production in Z-decay. We have found that the four-jet cross section of the process $Z \to \overline{q}q\Phi\Phi$ is approximately 15% of standard QCD four-jet cross section $Z \to \overline{q}q\overline{q}^{'}q'$ which in turn is around 5% of the total four-jet cross section [8]. So the discovery at LEP of light scalar octets by the measurement of the four-jet cross section is rather problematic. For the scalar masses $M \geq O(10)Gev$ the scalar octet decaying into two gluons produces two gluon jets, so we shal have 6 jet events with 4 gluon jets. Unfortunately we don't know rather well 6 jet cross sections. We can estimate that 6 jet cross section is $\alpha_s^2 \sim 0.01$ smaller than 4-jet cross section, so the standard 6 jet QCD cross section is of the same order of magnitude as (at least for $M \sim 10Gev$) the 6 jet cross section due to the scalar octet decays. By the measurement of the differential 6 jet cross section

$$\frac{d\sigma^2}{dm_{12}dm_{34}} \tag{10}$$

(here $m_{12}^2 = (p_{1,jet} + p_{2,jet})^2$ and $m_{34}^2 = (p_{3,jet} + p_{4,jet})^2$ are the invariant two-jet square masses) it is possible to discover the scalar octets with masses $10Gev \leq M \leq 20Gev$ provided the accuracy in the determination of the two-jet invariant mass is less than 10% since in this case we earn additional factor $O(100)$ for the suppression of the background. So, it would be very interesting to consider the distributions of 6 jet events at LEP1 on the two-jet invariant masses. As I know there was not such analysis of LEP1 data.

Consider now the production of scalar octets at FNAL and LHC. The corresponding lowest order predictions for the parton cross sections have the form

$$\frac{d\sigma}{dt}(\overline{q}q \to \Phi\,\Phi) = \frac{4\pi\alpha_s^2}{s^4}(tu - M^4)\,, \tag{11}$$

$$\begin{aligned}\frac{d\sigma}{dt}(gg \to \Phi\Phi) \quad = \quad & \frac{\pi\alpha_s^2}{s^2}(\frac{7}{96} + \frac{3(u-t)^2}{32s^2})(1 + \frac{2M^2}{u-M^2} + \frac{2M^2}{t-M^2} + \\ & \frac{2M^4}{(u-M^2)^2} + \frac{2M^4}{(t-M^2)^2} + \frac{4M^4}{(t-M^2)(u-M^2)})\,,\end{aligned} \tag{12}$$

$$\sigma(\overline{q}q \to \Phi\Phi) = \frac{2\pi\alpha_s^2}{9s}k^3\,, \tag{13}$$

$$\sigma(gg \to \Phi\Phi) = \frac{\pi\alpha_s^2}{s}(\frac{15k}{16} + \frac{51kM^2}{8s} + \frac{9M^2}{2s^2}(s - M^2)ln(\frac{1-k}{1+k}))\,, \tag{14}$$

where $k = (1 - \frac{4M^2}{s})^{\frac{1}{2}}$. We have calculated the cross sections for the production of scalar octets at FNAL and LHC using the results for the parton distributions of ref.[9], namely, in our calculations we have used set 1 of the parton distributions. We have found that at LHC the main contribution ($\geq 95\%$) comes from the gluon annihilation into two scalar octets $gg \to \Phi\Phi$, whereas at FNAL gluon-gluon and quark-antiquark annihilation cross sections are comparable. The results of our calculations are presented in tables 2 and 3. For light scalar octets two gluon and quark-antiquark annihilations into two scalar octets give additional contribution to the two-jet cross section. However, this additional

contribution is rather small. For instance, the cross section for gluon-gluon scattering is [10]

$$\frac{d\sigma}{dt}(gg \to gg) = \frac{9\pi\alpha_s^2}{2s^2}[3 - \frac{tu}{s^2} - \frac{su}{t^2} - \frac{st}{u^2}] \tag{15}$$

Even for the most favorable case $t = u = -\frac{s}{2}$ the cross section (12) is 20 times less than gluon-gluon cross section (15). So the perspective to detect light scalar octets by the measurement of the two-jet cross sections looks hopeless. For rather big values of the scalar octet mass ($M \geq O(50)Gev$) the scalar octets decay into two gluons that leads to the four-jet events. The cross section for the scalar octet production for $M \sim 100Gev$ is $O(10^{-3})$ of the standard QCD two-jet cross section and it is (10 - 100) times smaller than the standard 4-jet QCD cross section. So by the measurement of the two-jet invariant masses like as in the case of LEP1 it is possible (if we know two-jet invariant masses with an accuracy better than 10%) to earn additional factor ~ 100 and to discover or at least to obtain lower bound on the scalar octet cross section for scalar octet masses $O(several)Gev \leq M \leq O(200)Gev$ at LHC.

It should be noted that scalar octets naturally arise in models with compactification of additional space dimensions [11]. As a toy model consider 5-dimensional QCD with massless quarks. Let us compactify the 4 th coordinate x_4 on the torus, i.e. impose the boundary conditions

$$A_M(x_\mu, x_4) + R_c) = A_M(x_\mu, x_4), \tag{16}$$

$$\Psi(x_\mu, x_4 + R_c) = \Psi(x_\mu, x_4) \tag{17}$$

After compactification we obtain at tree level massless gluon field $A_\mu(x_\mu)$, massless scalar octet $\Phi(x_\mu) = A_4(x_\mu)$, massless quarks plus the infinite tower of massive excitations of gluons and quarks with masses proportional to the inverse compactification radius R_c^{-1} . At quantum level massless octet $\Phi(x_\mu)$ acquire a mass $M \sim (O(\frac{\alpha_s}{2\pi}))^{0.5}R_c^{-1}$. So, for the models with big compactification radius $R_c^{-1} \leq 10Tev$ we expect that the scalar octet mass is less than $O(1)Tev$. Due to the interaction of scalar octet with the excitations of quarks scalar octet will decay at one loop level mainly into two gluons, however the branching ratio of the colourless bound state of scalar octet and gluons into two photons is not small and one can estimate that it is $Br(\Phi g \to \gamma\gamma) \sim O((\frac{\alpha_{em}}{\alpha_s})^2) \sim O(10^{-2})$. So we shall have events with two jets and two photons (one of the producing octet bound state decays into two gluons and the other one decays into two photons). Therefore the search for the Higgs boson at LHC using two photon mode is simultaneously the search for the scalar octets, however for the scalar octet case besides two photons we shall have in addition two jets that makes the search for the scalar octets much more easier than the search for the Higgs boson. For instance, for the integral luminosity $10^5(pb)^{-1}$ we expect for the scalar octet mass $M = 200Gev$ and $M = 700Gev$ $O(10^6)$ and $O(10^3)$ events with two photons and two jets correspondingly , so it would be possible to discover at LHC the scalar octets with masses lighter than 1 Tev.

To conclude, in this note we have studied the perspectives of the discovery of scalar octets at LEP1, FNAL and LHC. New hadrons composed from scalar octets are rather longlived even for high scalar octet masses. We have found that the existence of light scalar octets with the masses $O(several)$ Gev don't contradict to the existing experiments.

Heavy scalar octets could be discovered at LHC, FNAL or LEP by the measurement of the distributions of the differential cross sections on the invariant two-jet masses. Scalar octets naturally arise in models with compactification of additional space dimensions. In such models the branching ratio of scalar octet and gluon colourless bound state into two photons is $O(10^{-2})$ so scalar octets in such models could be detected by the search for the events with two photons and two jets.

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Table 1. The branching $B = 10^3 \cdot \Gamma(Z \to \overline{q}q\Phi\Phi) \cdot ((\Gamma Z \to hadrons))^{-1})$ for different scalar octet masses

M(Gev)	2	5	10	15	20	25	30	35
B	7.25	1.63	0.22	0.037	0.0058	0.00078	$7.0 \cdot 10^{-5}$	$2.7 \cdot 10^{-6}$

Table 2. The cross section $\sigma(pp \to \Phi\Phi + ...)$ in pb for different values of octet masses and normalization pointμ at LHC

M(Tev)		2	1.5	1	0.75	0.5	0.3	0.2
σ	$\mu = 3.75Tev$	0.00024	0.004	0.093	0.60	6.0	76.3	786.4
σ	$\mu = 2M$	0.00026	0.0042	0.10	0.69	7.40	84.3	701.4
σ	$\mu = 4M$	0.00028	0.0043	0.092	0.619	6.6	91.0	832

Table 3. The cross section $\sigma(\overline{p}p \to \Phi\Phi + ...)$ in pb for different values of octet masses and normalization point μ at FNAL.

M(Gev)		300	250	200	150	125	100	75	50
σ	$\mu = 450Gev$	0.014	0.07	0.40	3.0	9.9	38.8	198.4	1620
σ	$\mu = 2M$	0.013	0.074	0.42	3.56	10.8	52.4	267.4	2940
σ	$\mu = 4M$	0.014	0.058	0.33	2.8	9.6	40.3	208.3	1782

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